BNFL Inc.

Document title:

Approach for Ensuring Compliance with the TWRS-P Radiation Exposure Standards under Earthquake Conditions

Department: Safety & Regulatory Programs

Contract title: TWRS Privatization

Contract number: DE-AC06-96RL13308

Author(s): Martin McCann William White

Document Number: PL-W375-RU00002, Rev. 0

Checked by: Paul Amico Richard Smith

Date of issue: March 17, 1999

Issue status: Approved

Approved by: Don Edwards

Approver's position: Safety & Regulatory Programs Manager

Approver's signature

BNFL Inc.
TWRS-P Project
2940 George Washington Way
Richland, WA 99352
United States of America
Tel: 509 371 3000
Fax: 509 371 3001

History sheet

Rev	Date	Reason for revision	Revised by
0	03/17/1999	Initial Issue	

Contents

TABLE

FIGURES

Contents

1. Introduction

To ensure the safety of the TWRS-P Facility in the event of an earthquake, selected facility systems, structures and components (SSCs) that are important-to-safety will be designed to Performance Category 3 (PC-3) criteria as provide in DOE-STD-1020-94 (DOE, 1996; BNFL, 1999). SSCs designed to PC-3 criteria will be designed for a Design Basis Earthquake (DBE) ground motion that has a frequency of exceedance of $5x10^{-4}$ per year.

Due to the presence of radioactive materials that will be processed and stored at the TWRS-P Facility, the project Safety Requirements Document (SRD) (BNFL, 1998) includes established radiation exposure standards (RES) that provide radiological exposure levels for facility and co-located workers and for the public. The RES are further categorized in terms of annual frequency and require that accident occurrence frequencies as low as 10^{-6} per year be considered. Seismic Probabilistic Risk Analysis (PRA) will be used to address events with annual frequencies less than $5x10^{-4}$.

The purpose of this document is to describe an approach for demonstrating that the TWRS-P Facility seismic design complies with the project RES including earthquakes larger than the DBE. The compliance approach for earthquakes will involve a seismic probabilistic risk analysis (PRA) of the TWRS-P Facility that will:

1. Provide an explicit demonstration of the compliance of the facility seismic design with the RES. It will show the frequency of occurrence and magnitude of radiation exposure of facility and co-located workers and the public associated with the performance of the TWRS-P Facility as a result of a seismic event are sufficiently low that all RES are met.

2. Evaluate the performance of the TWRS-P Facility for ground motions beyond the Design Basis Earthquake (DBE).

3. If necessary, provide specific guidance for the seismic design of facility systems, structures, and components (SSCs) in order that compliance with the RES is achieved.

The approach is similar to other applications (Kennedy and Short, 1994; Kennedy, 1997; Amico, et. al., 1995) in which compliance with a seismic performance goal or risk criteria must be demonstrated.

Section 2 summarizes the seismic design features of the TWRS-P Facility and the RES requirements that must be satisfied. This is followed in Section 3 with a description of the TWRS-P Project compliance approach for earthquakes. Section 4 discusses how each element of the seismic PRA will be carried out as part of the iterative analysis. Section 5 summarizes the products of the TWRS-P Project compliance analysis for earthquakes. References are listed in Section 6.

2. Seismic Design Basis and Radiation Exposure Standards

2.1. Overview

This section summarizes the standards that apply to the seismic design of the TWRS-P Facility and the level of safety that must be provided for facility and co-located workers and the public in terms of their exposure to radiological hazards.

2.2. TWRS-P Facility Seismic Design Basis

As noted in Section 1, the TWRS-P Facility seismic design will be in accordance with DOE-STD-1020-94 (DOE, 1996; BNFL, 1999). SSCs that have seismic safety functions will be assigned to Performance Category 3 (PC-3) and, as such, will be designed to withstand the loads imposed by the DBE. Per DOE-STD-1020-94, the DBE for PC-3 is defined as a ground motion that has a frequency of exceedance of $5x10^{-4}$ per year. For the TWRS-P Facility site, a 0.26g peak ground acceleration (PGA) has been adopted as the ground motion associated with this exceedance frequency (BNFL, 1999).

In addition to defining the selection of the DBE, DOE-STD-1020-94 also provides guidance for the design and evaluation of SSCs. The purpose of these guidelines is to provide for seismic margins (conservatisms) in the design of individual SSCs such that the performance goals specified in DOE-STD-1020-94 are achieved. With the exception of a few changes (which are conservative), the TWRS-P Project seismic design approach complies with the design and evaluation guidelines of DOE-STD-1020-94.

2.3. Radiological Exposure Standards

In the event an earthquake damages one or multiple SSCs at the TWRS-P Facility, the potential exists that radiological materials may be released. The TWRS-P Project Safety Requirements Document (SRD) establishes radiological exposure standards that provide for the safety of facility and co-located workers and the public. The RES that are applicable to this seismic PRA effort are provided in Table 1.

As shown in Table 1, the RES are provided in terms of the frequency per year. For this evaluation, this is taken to be the annual frequency that the listed radiological exposure levels can occur. For instance, exposure levels of 5 rem for facility and co-located workers must not occur more frequently than 10^{-2} per year. Similarly, exposure levels that exceed 25 rem for facility and co-located workers and the public must have a frequency of occurrence per year less than10^{-6}. In addition, the exposure standards are defined per initiating event (e.g., seismic, wind, external flood). This format is similar to DOE-STD-1020-94, which also establishes SSC performance goals in terms of individual natural phenomena (i.e., external initiating events).

2.4. Demonstrating Compliance

The purpose of the TWRS-P Project compliance analysis will be to show that the facility seismic design satisfies the RES. To accomplish this, it must be demonstrated that the frequency of occurrence of radiological exposure as a result of an earthquake and damage to the TWRS-P Facility satisfies the criteria provided by the project RES. However, the seismic design of the TWRS-P Facility, which is applicable to the design and evaluation of individual SSCs (e.g., High Level Waste Building, Pre-Treatment Building) and is carried out to meet the criteria of DOE-STD-1020-94, is silent on the performance of the facility as a system of SSCs, on its performance for ground motions beyond the DBE, and on facility and co-located worker and public safety. Consequently, the seismic design process that is implemented to satisfy DOE-STD-1020-94 does not provide a direct basis to show that the project RES will be satisfied. Therefore, to demonstrate compliance, an iterative seismic PRA is the vehicle that will be employed on the Project.

The purpose of the seismic PRA for the TWRS-P Facility will be to estimate the frequency of occurrence of a seismically initiated exposure of facility and co-located workers and the public to radiological hazards that could challenge the Project's RES. The analysis will:

1. Evaluate the performance of the TWRS-P Facility for ground motions beyond the DBE.

2. Account for the seismic margins above the DBE provided in the design of individual SSCs.

3. Model the TWRS-P Facility as a system of SSCs accounting for redundancy in design, safety and mitigation systems.

4. Analyze the accident sequences (e.g., combinations of multiple SSC failures) that could occur during an earthquake and lead to radiological release and exposure.

The following section describes the compliance approach that addresses these factors.

Table 1. Applicable Parts of the TWRS-P Project Radiological Exposure Standards { TC "1. Applicable Parts of the TWRS-P Project Radiological Exposure Standards" \f T }(BNFL, 1998)

Description (Event Type)	Frequency of Occurrence (yr^{-1})	Facility Worker	Co-located Worker	Public
Anticipated	10^{-2} - 10^{-1}	$\leq$5 rem/event	$\leq$5 rem/event	$\leq$0.10 rem/event
Unlikely	10^{-4} - 10^{-2}	$\leq$25 rem/event	$\leq$25 rem/event	$\leq$5 rem/event
Extremely Unlikely	10^{-6} - 10^{-4}	$\leq$25 rem/event	$\leq$25 rem/event	$\leq$25 rem/event

3. Seismic Compliance Approach

3.1. Overview

This section describes the TWRS-P Project approach to demonstrate that the facility seismic design complies with the project radiation exposure standards. The approach involves a seismic PRA for the TWRS-P Facility that models the accident sequences that may be initiated by an earthquake and result in radiological release and exposure of facility and co-located workers and the public. Implementation of the TWRS-P Facility seismic model will be conducted in an iterative manner in which resources are focused on the factors that are important to determining the frequency and magnitude of radiological exposure and to demonstrating RES compliance, as the analysis progresses.

This section describes the elements and steps in the compliance approach. This is followed by Section 4, which discusses how the elements of the seismic PRA will be implemented.

3.2. Project RES and Seismic Risk

The project RES establishes acceptance criteria for facility and co-located worker and public exposure to radiological hazards associated with TWRS-P Facility operations.

In conducting the compliance evaluation, the RES frequency of occurrence and radiological exposure levels will be treated as limits or bounds for earthquakes. Due to the conservative nature of the iterative PRA to be conducted (described below), even if the RES are met exactly, there will remain a considerable margin of safety such that the 'true' risk of exposure from a seismically initiated accident will be lower than the calculated results.

3.3. TWRS-P Facility Seismic PRA

The seismic PRA for the TWRS-P Facility will involve the following elements:

1. Seismic Hazard Analysis – quantifies the frequency of occurrence per year of earthquake ground motions at a site.

2. Seismic Fragility Analysis – quantifies for individual SSCs the conditional probability of failure as a function of levels of earthquake ground motion, accounting for structure response and capacity (e.g., DBE, material strength, seismic margins above the DBE).

3. Systems Model – consists of a logic model using event and fault trees that describe the accident sequences (e.g., combinations of SSC failures) that can lead to release of radiological materials. The system model considers facility safety systems, actual conditions, and redundancies that have been incorporated in the TWRS-P Facility design.

4. Radiological Release and Dispersion Analysis – this involves an evaluation of the magnitude and release rate of radiological material as a result of damage to specific SSCs in an accident sequence and the dispersion of this material in the facility and outside. The estimate of radiological releases is based on the nature and extent of damage to SSCs (e.g., cracking of building exterior walls) that have failed in each accident sequence.

5. Risk Quantification – the elements of the analysis are combined to estimate the magnitude of radiological releases and their frequency of occurrence.

Ground motions that can occur at the TWRS-P Facility depend on the magnitude of future earthquakes and their proximity to the site. These ground motions may range from less than the DBE, to higher levels as defined by the site seismic hazard curve. As a result, the quantification of the frequency of seismically initiated radiological release and exposure will be carried out for the full range of ground motions at the TWRS-P Facility site.

Section 4 describes how each element in the TWRS-P Facility seismic PRA will be conducted.

3.4. Implementation Strategy

The following subsections describe the implementation of the compliance approach.

3.4.1. TWRS-P Facility - Minimum Required Seismic Capacity

As a first step to conduct a seismic PRA for the TWRS-P Facility, a screening criterion will be developed. The purpose of the screening criterion is to identify the SSCs that have sufficiently high seismic capacity and therefore can be screened out from further evaluation. The screening criterion will be determined by using the RES and the seismic hazard and back calculating a bounding system facility curve. This is the seismic capacity that the TWRS-P Facility, as a system of SSCs, must have in order to satisfy the exposure requirements (see Figure 1). If the seismic fragility curve for the TWRS-P Facility (as a system of SSCs) lies to the right of the bounding curve (e.g., has high seismic capacity), the RES are satisfied (i.e., the frequency of a seismically initiated accident and release will be less than the listed exposure levels). If however, the seismic fragility curve for the TWRS-P Facility lies to the left of the bounding curve (i.e., has low seismic capacity), the frequency of radiological release and exposure may exceed the RES acceptance criteria.

3.4.2. Initial Seismic Screening

The bounding TWRS-P fragility curve will be used to develop a tool to screen individual SSCs. This screening tool will serve as a means to defensibly screen out components whose failure will not be a significant contributor to the frequency of seismically initiated accidents or radiological release (see Figure 1). As such, these components are screened out from further evaluation and are not considered in the seismic PRA. Alternatively, components whose seismic capacity is less than or not significantly higher than the bounding TWRS-P fragility curve (see Figure 1), will require further evaluation and incorporation into the seismic PRA. This approach has been used successfully in nuclear power plant seismic margin and risk studies (EPRI, 1991; Reed and Kennedy, 1995) and is considered to be appropriate for both the types of SSCs and the seismic hazards associated with the TWRS-P Facility.

3.4.3. Iterative Seismic PRA

Following the initial screening of SSCs, the seismic systems model for the TWRS-P Facility is developed. Once the system event and fault trees are constructed, the seismic risk associated with the TWRS-P Facility operations can be quantified.

A comprehensive seismic PRA for the TWRS-P Facility requires a demanding effort (e.g., determine SSC seismic fragility parameters, estimate the release and dispersion of radioactive materials). A less demanding, more focussed approach is employed by conducting the seismic PRA in an iterative manner. For purposes of demonstrating compliance with the project RES, an iterative approach is advantageous since it provides the flexibility to focus resources on those elements or parameters in the analysis that are important-to-safety (e.g., dominant contributors to the seismic risk of release and exposure).

The initial risk quantifications (i.e., estimate of the frequency of seismically initiated accidents and radiological release and exposure) will be made on the basis of:

1. Preliminary estimates of SSC median seismic capacities based on the DBE design requirements and defensible, conservative estimates of seismic margins above the DBE

2. Conservative estimates of the radiological release for each accident sequence

3. Conservative estimates of random (non-seismically initiated) event probabilities and operator/worker error probabilities.

If compliance is demonstrated as a result of these initial quantifications, the analysis is complete. However, due to the conservatism of the inputs, this may not be the case. At this point, a systematic review of the seismic PRA results is conducted to identify the accident sequences and the SSC failures that are the dominant contributors to seismic risk (e.g., whether the release dominated by the failure of a single tank or is it a cumulative result of multiple failures, involving smaller inventories). This approach is the same as discussed at the January 8, 1999 meeting with the DOE Regulatory Unit, particularly with respect to the assessment of initial SSC fragility parameters (Kennedy, 1999).

Based on a review of the initial seismic PRA results, alternatives are identified to improve the estimate of the TWRS-P Facility seismic risk. Alternatives that are considered will vary depending on:

1. The specific RES that is not met (e.g., for facility or co-located workers, or for the public)

2. The accident sequences and the SSCs failures that are the dominant contributors

3. The nature of the damage to the SSCs that is expected (e.g., through wall cracking of building walls)

4. The magnitude of the deficit (the difference between the RES and the calculated seismic exposure) that must be eliminated.

For most components in the seismic model, the initial estimates of seismic fragility parameters will be conservative (i.e., the median capacities will be underestimated). (Note: for a certain limited number of SSCs such as the connection to off-site power, realistic, best estimates of fragility parameters will be used.) As a result, early iterations are likely to focus on estimating more realistic, component specific fragility parameters for those SSCs that are important contributors.

In addition, subsequent iterations may involve making improved (more realistic) estimates of the magnitude of radiological releases depending on the conservatism in the exposure levels that are determined and the nature and extent of SSC damage that is expected to occur.

Lastly, it may be necessary to consider modifying the seismic design of SSCs with seismic safety functions in order for compliance to be achieved. In this case, a seismic capacity or a performance level (e.g., limiting displacement) may be specified for an SSC.

Several iterations could be required to demonstrate compliance.

3.5. Compliance Analysis Steps

Figure 2 shows a schematic of the steps involved in the compliance analysis. The individual steps are listed below:

1. Establish the basis for screening TWRS-P Facility SSCs that have high seismic capacity. As part of this step the TWRS-P Facility bounding fragility curve is determined.

2. Develop an inventory of the TWRS-P Facility SSCs whose failure could lead to a release of radioactive material.

3. Estimate initial seismic fragility parameters (see Section 4) for the SSCs whose failure can lead to release.

4. Screen the initial SSC seismic fragility estimates according to the screening criterion.

5. Develop a TWRS-P Facility seismic systems model that identifies the accident sequences that can result in radiological release. Also, determine the probabilities of non-seismic failures that can occur (e.g., random failure of a diesel generator to start).

6. For each accident sequence in the systems model, determine the magnitude of the radiological release that could occur (based on the SSCs that have failed) and the exposure of each receptor population that may result.

7. Perform an initial risk quantification for the TWRS-P Facility based on the initial SSC fragility parameters and the radiological release and exposure estimates.

8. Review the risk analysis results to determine if the frequency and magnitude of radiological exposure satisfies the project radiation exposure standard. If the standard is satisfied for facility and co-located workers and the public, compliance is demonstrated.

   If compliance is not demonstrated, a systematic review of the results is conducted to identify the accident sequences and the SSC failures that are the primary contributors to the TWRS-P Facility seismic risk.

9. Based on the events (e.g., SSC failures) that are the dominant contributors to the exceeding the exposure standards, a strategy(s) is selected to mitigate the offending accident sequences. Strategy options include:

   a. Develop more realistic fragility parameters (i.e., remove conservatisms in the initial estimate of the SSC median capacities) for critical components.

   b. Develop realistic performance criteria for modeling damage that leads to radioactive release.

   c. Develop realistic radiological release estimates based on the expected damage that may occur to critical SSCs.

   d. Incorporate systems or operational strategies designed to reduce exposure to possible releases.

   e. Modify the seismic design of critical SSCs.

   In all cases, the strategy chosen will be defensible; that is, it will be supported by appropriate analysis, expert judgment, experiment, or actual experience.

10. Reevaluate the TWRS-P Facility seismic risk (Step 7) with the alternative strategy(s) from Step 9.

11. Iterate (from Step 8) until compliance with the RES is demonstrated.

The iterative seismic PRA is an efficient means to demonstrate compliance with the project radiation exposure standards. As noted, the purpose of the compliance analysis is to show that the TWRS-P Facility seismic design satisfies the RES. Because the iterative analysis is concluded once compliance is demonstrated, the ‘true’ seismic risk (e.g., frequency of radiological exposure) will be lower than the final calculated results.

Section 4 discusses the steps involved in carrying out each element of the seismic PRA for the TWRS-P Facility and sources of information that are available.

Figure 1. Illustration of a TWRS-P Facility Bounding Seismic Fragility Curve{ TC "1. Illustration of a TWRS-P Facility Bounding Seismic Fragility Curve" \f F }

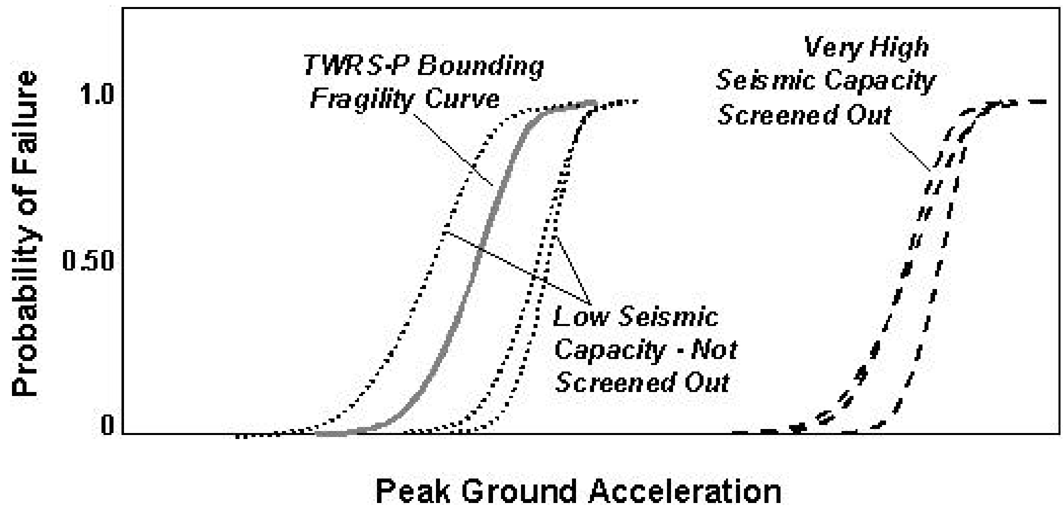
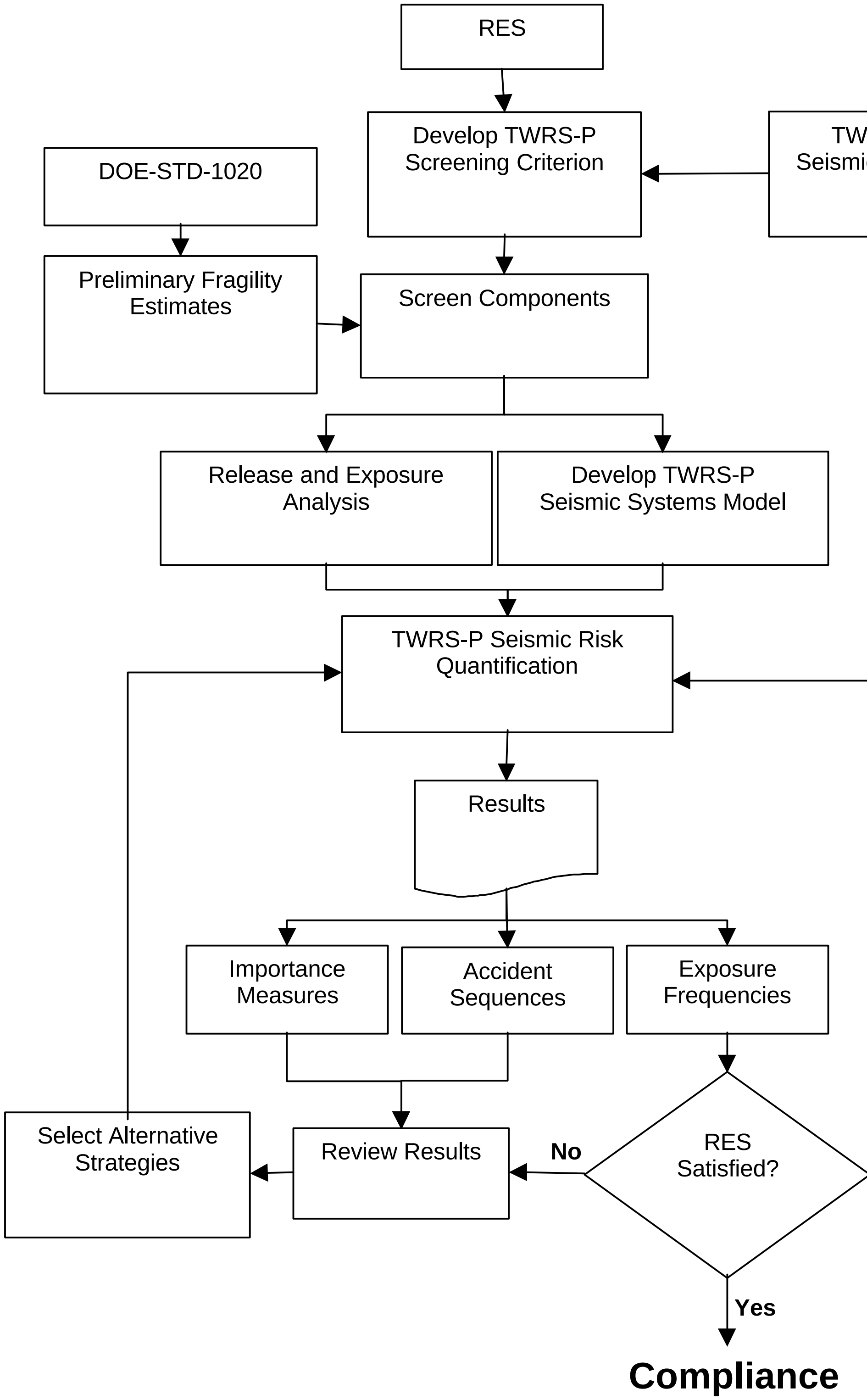


Figure 2. Diagram of the Steps in the TWRS-P Project Compliance Analysis{ TC "2. Diagram of the Steps in the TWRS-P Project Compliance Analysis" \f F }



4. Seismic Probabilistic Risk Analysis

4.1. Overview

The seismic PRA for the TWRS-P Facility will be performed to estimate the mean frequency of seismically initiated accidents and radiological exposure of facility and co-located workers and the public. To calculate mean results, the uncertainty in the individual parts of the analysis will be used (e.g., seismic hazard, seismic fragility). However, due to the iterative, conservative nature of many of the inputs that will be used in the analysis a 'conservative' estimate of the mean will be calculated.

The following subsections describe each part of the seismic analysis and how it will be conducted as part of the iterative PRA for the TWRS-P Facility compliance analysis.

4.2. Seismic Hazard Analysis

A probabilistic seismic ground motion hazard analysis (PSHA) has been conducted for the TWRS-P Facility site (Geomatrix, 1996). The Geomatrix study involved an extensive analysis of the regional and local tectonics and the uncertainty in the characterization of earthquake occurrences and ground motion. For purposes of the TWRS-P Facility compliance evaluation, the PSHA provides an estimate of the mean frequency of occurrence of earthquake ground motions.

Currently, the TWRS-P Facility site seismic hazard curve is defined for a maximum ground motion of about 0.9g PGA and a frequency of exceedance of approximately 10^{-5} per year. For purposes of the seismic PRA, it is necessary to estimate the occurrence of seismically initiated accidents with annual frequencies down to 10^{-6}. To accomplish this, additional PSHA calculations will be performed to extend the site hazard curve to higher ground motions and lower frequency levels.

4.3. Systems Analysis

In this part of the seismic PRA, a logic model will be developed using event and fault tree techniques to describe the accident sequences that could lead to a release of radioactivity and exposure of facility and co-located workers and the public. The systems model will be developed on the basis of the TWRS-P Facility process design, safety systems, facility layout, and operating procedures.

4.4. Fragility Analysis

The purpose of the seismic fragility analysis is to determine the conditional probability that a SSC will fail as a function of earthquake ground motion. A fragility curve is generally defined by a lognormal distribution that has two parameters, a median and logarithmic standard deviation. The fragility curve is S-shaped. At low ground motions, the conditional probability of failure is low. As ground motions increase, the conditional probability of failure increases, until at very high ground motions, failure is certain (see Figure 1). The preliminary estimate of the median value of the fragility curves will use the method suggested by Kennedy (Kennedy, 1999):

$$C_{50\%} = 1.5(F_{\mu D})(DBE)e^{1.282\beta}$$

β = Composite Logarithmic Standard Deviation parameter of the component fragility

$F_{\mu D}$ = Inelastic energy absorption factor

As part of the TWRS-P Project compliance analysis for earthquakes, an iterative approach will be used to estimate the seismic fragility parameters of individual SSCs. This approach has been successful in the past and it provides the flexibility to concentrate the analysis effort. Initial estimates of SSC fragility parameters will take advantage of past seismic PRA experience (principally from the nuclear power industry), earthquake performance data, and testing experience (EPRI, 1991; Kennedy and Reed, 1994; SSRAP, 1992; Merz, et al, 1991a,b; Bandyopadhyay, et al., 1986, 1987, 1988, 1991; Holman, et al., 1986, 1989). Using this information, it is possible to make credible, conservative estimates of TWRS-P Facility SSC fragility parameters (i.e., the median seismic capacity and logarithmic standard deviation) (EPRI, 1991; Kennedy and Reed, 1994; Kennedy, 1998) with limited effort. These estimates will consider:

- The TWRS-P Facility DBE.
- Seismic design and evaluation criteria provided in DOE-STD-1020-94 (as modified by the Project seismic design approach), which establishes a margin between the DBE and the acceptance criterion.
- Estimated seismic margins for industrial and nuclear power plant equipment.

In addition to the above, the estimate of seismic fragility parameters will account for the location of components in buildings (in-structure response) and soil-structure interaction effects (i.e., structure embedment). Estimates of the randomness and uncertainty in SSC performance (e.g., the composite logarithmic standard deviation of the fragility curve) will be based on the results of past seismic PRAs.

Following the initial risk quantifications, the important contributors to risk will be identified. For SSCs whose failure is important, improved estimates of their seismic capacity can be made (increased) by removing additional conservatism in the initial estimate, or by defining the actual damage that is required to produce a radiological release (e.g., throughwall cracking of a building and the ground motion that will cause it).

4.5. Radiological Release and Dose Analysis

For each accident sequence modeled in the TWRS-P Facility seismic systems analysis, an assessment will be made of the radiological release that will occur and the exposure of receptor populations. In the initial evaluation, a bounding estimate of the radiological release that may occur for each accident type will be made. A bounding approach is efficient, but at the same time conservative (Amico, et. al., 1995). The dispersion analysis will involve a best estimate of the exposure of each receptor population to radiological hazards.

The results of the initial risk calculations will be used to determine if the conservatism in the bounding analysis should be revisited for all or certain accident sequences.

4.6. Risk Quantification

In the compliance analysis, the seismic risk calculations will be performed to estimate the mean frequency of occurrence of seismically initiated accidents and exposure. The estimate of seismic risk is obtained by combining the parts of the PRA to determine the frequency of seismically initiated accidents and radiological release. The quantification will be performed using the SHIP code (JBA, 1994). The SHIP code is a risk quantification tool specifically designed for external event PRAs.

5. Compliance Analysis Products

The TWRS-P Facility compliance approach for earthquakes will provide the following primary results:

- Explicit demonstration of the TWRS-P Facility seismic design compliance with the RES.
- Explicit evaluation of the TWRS-P Facility performance for ground motions beyond the DBE.
- An estimate of the “required” seismic capacities that must be provided for TWRS-P Facility SSCs in order to meet the RES.

In addition to demonstrating compliance with the RES, the TWRS-P Facility seismic PRA model may serve the project in other capacities as well. These may include:

- The TWRS-P Facility seismic PRA model can be used throughout the design process as a means to guide/support design decisions (e.g., changes to SSC physical layout) such that the final design remains in compliance with the RES.
- The model may provide insight to potential vulnerabilities (i.e., operational, structural) that can be avoided or remedied during the design process.
- If it becomes necessary to examine multiple seismic design alternatives, the seismic PRA model could be used to support an optimization evaluation (Youngblood, et. al., 1999).

6. References

Amico, P.J., B.P Tripathi, D.M. Pinkston, J.K. Kimball, “A Risk-Based Approach to Assigning Natural Phenomena Hazards (NPH) Performance Goals to Hazardous Facility Systems, Structures and Components,” Risk and Safety Assessments: Where is the Balance?, 1995 ASME-PVP Conference, Hawaii, June 1995.

Bandyopadhyay, K.K., et. al., “Seismic Fragility of Nuclear Power Plant Components,” prepared by Brookhaven National Laboratory for the U.S. Nuclear Regulatory Commission, NUREG/CR-4659, Vols. 1-4, Washington, D.C., 1986-1991.

BNFL, “TWRS-P Privatization Project: Safety Requirements Document,” BNFL-5193-SRD-01, Revision 1, BNFL, Inc., Richland, Washington, June 10, 1998.

BNFL, “TWRS-P Facility Design Basis Earthquake – Peak Ground Acceleration, Seismic Response Spectra, and Seismic Design Approach,” Revision 1 (draft), BNFL, Inc., Richland, Washington, February 12, 1999.

DOE, “Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities,” DOE-STD-1020-94, Change Notice 1, U.S. Department of Energy, Washington, D.C., January 1996.

Electric Power Research Institute, “A Methodology for Assessment of Nuclear Power Plant Seismic Margin (Revision 1),” NP-6041-SL, Palo Alto, California, 1991.

Geomatrix, "Probabilistic Seismic Hazard Analysis, DOE Hanford Site Washington," WHC-SD-W236-TI-002, Revision 1A, prepared by Geomatrix Consultants, Inc., San Francisco, California, for Westinghouse Hanford Company, Richland, Washington, October 1996.

Holman, G.S., et. al., "Component Fragility Research Program," prepared by Lawrence Livermore National Laboratory, NUREG/CR-4659, NUREG/CR-5470, U.S. Nuclear Regulatory Commission, December 1986.

Holman, G.S., et. al., "Component Fragility Research Program," prepared by Lawrence Livermore National Laboratory, NUREG/CR-5470, U.S. Nuclear Regulatory Commission, June 1989.

Jack R. Benjamin and Associates, Inc., "SHIP User's Manual," Menlo Park, CA, 1994.

Kennedy, R.P., "Establishing Seismic Design Criteria To Achieve An Acceptable Seismic Margin," Transactions of the 14th International Conference on Structural Mechanics in Reactor Technology, Lyon, France, August 17-22, 1997.

Kennedy, R.P., "Preliminary Seismic Fragilities Based Upon Seismic Design Criteria Prior to Having a Detailed Design," Presentation at the DOE-RU and BNFL/Bechtel Meeting, Richland, WA, January 8, 1999.

Kennedy, R.P., and J.W. Reed, "Methodology for Developing Seismic Fragilities," TR-103959, Electric Power Research Institute, Palo Alto, California, 1994.

Kennedy, R.P. and S.A. Short, "Basis for Seismic Provisions of DOE-STD-1020," UCRL-CR-111478, U.S. Department of Energy, April 1994.

Merz, K.L., "Generic Seismic Ruggedness of Power Plant Equipment," NP-5223, Revision 1, Electric Power Research Institute, Palo Alto, California, February 1991a.

Merz, K.L., "Seismic Ruggedness of Relays," NP-7147, Electric Power Research Institute, Palo Alto, California, February 1991b.

Reed, J.W. and R.P. Kennedy, "The Use of a Surrogate Element in Seismic Probabilistic Risk Assessment," AMSE PVP-Vol. 312, Honolulu, Hawaii, 1995.

Senior Seismic Review and Advisory Panel, "Use of Seismic Experience and Test Data to Show Ruggedness of Equipment in Nuclear Power Plants," SAND-92-0140, Sandia National Laboratories, prepared for the U.S. Nuclear Regulatory Commission, 1992.

Youngblood, R.W., "A Framework for Setting Seismic Design Criteria Using Prevention Analysis Techniques," Presentation at the DOE-RU and BN FL/Bechtel Meeting, Richland, WA, January 8, 1999.